2021

Evaluation of Liquid Ice Melting Additives for Winter Maintenance Applications

Erin Lammers
University of Kentucky, erin.lammers@uky.edu
Author ORCID Identifier:
https://orcid.org/0000-0002-6689-5009
Digital Object Identifier: https://doi.org/10.13023/etd.2021.300

STUDENT AGREEMENT:

I represent that my thesis or dissertation and abstract are my original work. Proper attribution has been given to all outside sources. I understand that I am solely responsible for obtaining any needed copyright permissions. I have obtained needed written permission statement(s) from the owner(s) of each third-party copyrighted matter to be included in my work, allowing electronic distribution (if such use is not permitted by the fair use doctrine) which will be submitted to UKnowledge as Additional File.

I hereby grant to The University of Kentucky and its agents the irrevocable, non-exclusive, and royalty-free license to archive and make accessible my work in whole or in part in all forms of media, now or hereafter known. I agree that the document mentioned above may be made available immediately for worldwide access unless an embargo applies.

I retain all other ownership rights to the copyright of my work. I also retain the right to use in future works (such as articles or books) all or part of my work. I understand that I am free to register the copyright to my work.

REVIEW, APPROVAL AND ACCEPTANCE

The document mentioned above has been reviewed and accepted by the student's advisor, on behalf of the advisory committee, and by the Director of Graduate Studies (DGS), on behalf of the program; we verify that this is the final, approved version of the student's thesis including all changes required by the advisory committee. The undersigned agree to abide by the statements above.

Erin Lammers, Student

Dr. Reginald Souleyrette, Major Professor

Dr. L. Sebastian Bryson, Director of Graduate Studies

EVALUATION OF LIQUID ICE MELTING ADDITIVES FOR WINTER MAINTENANCE APPLICATIONS

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering in the College of Engineering at the University of Kentucky

By

Erin Elizabeth Lammers

Lexington, Kentucky

Director: Dr. Reginald R. Souleyrette, Professor of Civil Engineering

2021

https://orcid.org/0000-0002-6689-5009

ABSTRACT OF THESIS

EVALUATION OF LIQUID ICE MELTING ADDITIVES FOR WINTER MAINTENANCE APPLICATIONS

Winter weather can often pose difficulties for transportation agencies as they work to clear roads of snow and ice quickly so that motorists can travel safely and efficiently. Kentucky has made efforts to maximize efficiency within its winter maintenance program by focusing on optimized equipment usage and personnel time management. This study's objective was to evaluate novel anti-icers and calculate how their performance compared to the current performance of brine and calcium chloride mixture. New brine additives claim to offer better results, but there is very little guidance about how to systematically evaluate new anti-icers. The author developed a testing methodology that could be performed in a laboratory setting to evaluate an anti-icer's ability to "undercut", or break the bond between pavement and ice. Four products were tested, as well as evaluated for price per lane mile when the additives were diluted with brine. The report concludes with a brief analysis of the environmental impacts of the additives, including effects on infrastructure and biosystems. Lastly, a priority ranking table summarizes the findings and provides an approach for other agencies to make their own decisions regarding anti-icing materials.

KEYWORDS: Deicing, Anti-icing, Anti-icing chemicals, Ice Undercutting Test, Winter Maintenance, Snow and Ice Treatment Programs

Erin Lammers

07/21/2021

Date

EVALUATION OF LIQUID ICE MELTING ADDITIVES
FOR WINTER MAINTENANCE APPLICATIONS

By

Erin Elizabeth Lammers

Dr. Reginald Souleyrette

Director of Thesis

Dr. L. Sebastian Bryson

Director of Graduate Studies

07/21/2021

Date

ACKNOWLEDGMENTS

This thesis was an individual work but benefitted from the insight and direction of several people. Thank you to my thesis director, Dr. Reginald Souleyrette, as well as my thesis committee, Dr. Nikiforos Stamatiadis and Dr. Eric Green. Their feedback was invaluable and their time was much appreciated. Additionally, thank you to Jerry Pigman and Nancy Albright for direction on project development, and Teng Wang for help with data processing.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Winter weather can often pose difficulties for transportation agencies as they work to clear roads of snow and ice quickly so that motorists can travel safely and efficiently. Kentucky receives about fifteen to twenty inches of snowfall each year.[1] The Kentucky Transportation Cabinet (KYTC) typically expends between $40 million and $80 million per year on snow and ice removal and road treatment, including equipment, materials, and personnel.[2] In recent years, KYTC has made efforts to maximize efficiency within its winter maintenance program. Previous research projects have uncovered efficiencies in equipment usage and personnel time management by optimizing snow plow routes in each transportation district. Now, KYTC is interested in evaluating its program with regard to the materials applied to roadways. There are many ice-melting products on the market, but they have not been compared and evaluated. KYTC has proposed an in-depth assessment of anti-icing materials and contracted the Kentucky Transportation Center (KTC) to perform the work.

1.2 CHEMISTRY

Although they vary widely in performance, all ice melters work in generally the same way— they depress the freezing point of ice or snow and turn the mixture into a liquid or semi-liquid slush. As the ice melter dissolves in water (or snow), the foreign particles hinder the natural freezing process of liquid. Turning a liquid into a solid requires organization or alignment of the water molecules. Foreign particles obstruct that alignment, so it takes longer to organize into a solid state. Therefore, the freezing point is lowered. In general, the greater the concentration of foreign particles in water, the lower its freezing point (although there is a limit to this correlation.)[3]

Ice melters are often classified based on their eutectic temperatures. The eutectic temperature is the temperature at which a deicer solution remains in liquid state. It is usually expressed as a percent weight of the solution. The eutectic temperature varies as a function of concentration, which creates a unique “eutectic curve” for any given product.[4] In a eutectic curve, the horizontal axis represents a concentration in solution and the vertical axis represents the temperature. A single horizontal line across the graph represents the temperature at which both components of the mixture are solid. A curved line represents the liquid state, which can be interpreted as either the freezing process or the precipitating process. The point at which the solid and liquid lines intersect is the eutectic point.[5]

During the normal process of ice melting, the ice melter is diluted. When diluted, sometimes the solution may refreeze. Therefore, its eutectic temperature is lower than its actual working temperature. Its working temperature, or effective temperature, is the lowest temperature at which a given ice melter should be used for practical purposes. The effective temperature is usually determined through field experience and not a laboratory test. For example, calcium chloride’s eutectic temperature is -25 degrees Fahrenheit, but

KYTC maintenance personnel have experience with frequent freeze/thaw cycles of calcium chloride at temperatures as high as 20 degrees Fahrenheit. Factors that affect effective temperature include dilution, relative temperatures of pavement versus snow, UV absorption, and friction characteristics of the deicer. Several experiments have attempted to construct effective temperature curves that could replace eutectic temperature curves, as these may be more practical for users, but no standard has been established yet.[4]

There are two general classes of ice melters: chemical salts and fertilizer products. Solid chemical salts bore through ice or snow and form a strong brine solution. This brine spreads under the ice or hard-packed snow and "undercuts," breaking the bond to the surface. Once loose, the ice or snow is easily removed by mechanical means. Fertilizer products work in much the same manner, though they do not form a brine. They are soluble in water and the resulting solution acts by depressing the freezing point of snow and ice.[6] There is evidence that some fertilizer-based ice melters act as "cryoprotectants," which slow down the freezing process of water but do not actually lower the temperature at which it freezes. These cryoprotectants can produce misleading results in some simple laboratory tests but will not function well as an ice melter in the field.[4]

The same materials used for melting can be applied in anticipation of ice or snow, preventing future snow or ice from bonding to the surface. When materials are used in this way, they are referred to as anti-icing material. Both solid and liquid deicers can be used as anti-icers. Liquid additives are often added to the anti-icing material as well. These liquid additives may be chemicals or agricultural byproducts and are meant to increase the effectiveness of the material. It is much easier to prevent ice from forming rather than melting it later. Consequently, using liquid anti-icers or anti-icing additives can increase the efficiency of an agency's snow and ice program.

1.3 CURRENT PRACTICE

The goals of KYTC's snow and ice control program are to:

- Provide adequate traction on road surfaces
- Promote safe and timely driving conditions
- Provide uniformity of pavement conditions within the route priority system
- Account for economic and environmental factors

The ability to meet these goals depends at least partially on the materials that are chosen to treat the roads.

In Kentucky, as in most states, the response to winter storms usually has two phases. First, if conditions allow, roads are pre-wet with an anti-icing liquid before snowfall begins. Once snow is on the ground, trucks begin plowing the roads and treating them with solid salt.

For anti-icing, KYTC currently uses a mixture of brine and calcium chloride. This three-ingredient combination contains water, 23.3% sodium chloride ($NaCl$), and 5% liquid calcium chloride ($CaCl_2$). The sodium chloride brine is created at a 23.3% solution because that is the concentration at which salt brine has the lowest freezing point: -6 degrees

Fahrenheit. The liquid calcium chloride is created at a 32.2% concentration. Calcium chloride melts ice down to approximately -25 degrees Fahrenheit. Calcium chloride is fast acting and generates additional heat as it dissolves. Additionally, brine forms easily because it has hygroscopic properties that cause it to attract moisture from its surroundings.

According to industry standards, the brine and calcium chloride mixture should be spread at a rate of about one ounce per square yard. It is applied at temperatures between 20 and 35 degrees Fahrenheit and should be allowed time to dry before precipitation begins. In order to allow for the drying time, anti-icing materials should not be utilized during those winter storms in which rain turns to snow. During recent winters, more than a million gallons each of brine and calcium chloride were used for pre-wetting and anti-icing. For extreme winter weather conditions, as much as 2.5 million gallons of brine has been used in one season.[2]

1.4 PROBLEM STATEMENT

Kentucky has used the same methodology for decades to treat roads during inclement weather. Over that time, many other products have been introduced in the market. Evaluating new liquid additives could optimize Kentucky's snow and ice removal process.

New brine additives claim to offer better results. However, they have not been rigorously tested and therefore their effectiveness and overall value for improving snow and ice control is unknown. There are also logistical issues associated with the use of additives, such as the need for additional storage, as well as concerns about the safe handling and distribution of these additives at KYTC's 124 snow and ice maintenance facilities.

To that end, the objectives for this research were to evaluate the effectiveness, costs, and feasibility of incorporating new liquid anti-icing materials into the Cabinet's winter maintenance program. An innovative methodology was required to meet this objective, since existing tests have been mostly theoretical or too complex to recreate. This research aims to customize theory to a realistic laboratory application. If this research proves to be successful, KYTC can make an educated choice about their anti-icing materials and other agencies can use the methodology to evaluate their own series of anti-icing materials as well.

CHAPTER 2. LITERATURE AND PRODUCT REVIEW

Research began with a review of relevant literature and current agency and industry practices on snow and ice removal. The review achieved three main purposes:

1) Determine products that might be of interest and understand their ice-melting capabilities
2) Gain insight into common road treatment practices by surveying several other state departments of transportation (DOTs)
3) Find or develop a testing method for products of interest

2.1 PRODUCTS

There are hundreds of anti-icing products on the market. For the purpose of this research, anti-icing additives refer to the chemical products or commercial blends that are added to brine and applied before a winter storm. Typically, anti-icing additives are added to a brine solution in percentages that are recommended by the distributor. Agencies can choose additives that are non-proprietary chemical products or they can purchase trademarked commercial mixes. This section will detail both types of products and review some of the most common products currently offered.

2.1.1 *SODIUM CHLORIDE*

Sodium chloride (NaCl), also known as rock salt, is considered the original ice-melting product. Its use dates back to the 1930s in the United States. KYTC uses a 23.3% solution of sodium chloride with water as its main ice melting product. It melts ice in temperatures as low as -9 degrees Fahrenheit, which is a relatively high eutectic point but generally considered strong enough for Kentucky's weather.[7]

There are some major drawbacks to using sodium chloride — it damages concrete, asphalt, stone, and brick, quickly leading to road and bridge degradation. Sodium chloride that leaks into soil can adversely impact groundwater and nearby biosystems.[7] If sodium chloride leaks into bodies of water that are used for drinking water, the contaminants are not always removed in the water-treatment process.[8] It can also be lethal to pets, making it an unwise choice for streets in residential neighborhoods.[9]

2.1.2 *CALCIUM CHLORIDE*

Using calcium chloride as an ice-melter or additive is common practice across the United States. Calcium chloride salt ($CaCl_2$) can melt ice to a temperature as low as -29 degrees Fahrenheit.[7] It is unique among other ice melters because it is exothermic: while most other products rely on their surroundings for heat to generate a reaction, calcium chloride generates its own heat as it dissolves. A pound of calcium chloride can raise the temperature of a gallon of water by over 30 degrees Fahrenheit. Additionally, brine forms easily because it is hygroscopic, meaning it has the ability to attract moisture from its surroundings.[10]

The corrosiveness of calcium chloride is still being studied. In terms of metal corrosion, calcium chloride is likely more harmful than sodium chloride. This is because metal corrosion occurs when moisture in the environment and electrolytes in the salt interact at a critical humidity level. Because calcium chloride is hygroscopic, its critical humidity level is lower and needs less moisture to begin the corrosion process compared to some other ice melting products.[11] In terms of damage to pavements, scientists have speculated that the major source of salt-related pavement damage is due to frequent freeze/thaw cycles rather than the chemical properties of the salt itself. Therefore, ice melt products with lower freezing points reduce the number and frequency of freeze/thaw cycles the pavement endures during the winter months. Because calcium chloride has a lower eutectic point than sodium chloride, calcium chloride is considered safer over extended periods of time.[12]

The cost of calcium chloride is significantly greater than that of sodium chloride. Agencies must perform a cost-benefit analysis to determine priority between winter maintenance, equipment maintenance, and road surface maintenance.

2.1.3 *POTASSIUM CHLORIDE*

Potassium chloride (KCl) is a common ice melter for areas with vegetation. Potassium is a main ingredient in fertilizers so potassium chloride has been marketed as beneficial to plants. However, the potassium levels present in this anti-icer are significantly higher than the levels present in fertilizers. Overuse of fertilizers can be detrimental to plant life and aquatic life. Additionally, it still contains chloride, which is the main destructive element in many ice melting products.[13] Of the most common ice melters, potassium chloride is perhaps the least effective: it has a working temperature of about 20 degrees Fahrenheit.[14] Overall, its benefits do not outweigh the concerns and, considering its high eutectic point, it is not considered strong enough for Kentucky’s winters.

2.1.4 *AMMONIUM-BASED PRODUCTS*

Ammonium-based products, such as ammonium nitrate (NH_44NO_3), ammonium sulfate ($(NH_4)_2SO_4$), and urea ($(NH_2)_2CO$), can be effective as an ice-melter. Their working temperatures vary, but generally they melt in temperatures as low as 15 degrees Fahrenheit.[14] Many home-gardeners and some parks opt to use these products because they act as a fertilizer to their plants. However, ammonia-based products are detrimental to bodies of water because the organic content can elevate biological oxygen demand, threatening aquatic life.[15]

Another main disadvantage to ammonium-based products is the fact that they attack concrete: the ammonium creates sulfuric acid, quickly degrading concrete. It appears safe to use on asphalt though.[6] Kentucky’s road system contains a mix of concrete and asphalt roads, so ammonium-based products would require a lot of logistical organization. Additionally, Kentucky’s cold winter temperatures require a stronger anti-icer.

2.1.5 *SODIUM ACETATE*

Sodium acetate ($C_2H_3NaO_2$) is often used on airplane runways, so it has been considered for roadways as well. Sodium acetate can be applied in solid pellet form or as a highly soluble white powder. It is very effective, melting ice in temperatures as low as 0 degrees Fahrenheit. It works similarly to calcium chloride: it is fast-acting, exothermic, and hygroscopic.[16,17] These traits create an exponential melting rate, meaning the compound becomes more effective over time. Compared to many other ice-melting products, sodium acetate often requires fewer reapplications.[17]

It is relatively harmless to the environment because it is biodegradable[17] and the EPA considers it a "low-concern" compound.[16] Since it is not chloride-based, it does not cause corrosion of metals or road materials.[11] In fact, it acts as a concrete sealant when dry, protecting the surface from the often-harmful effects of weather and other anti-icers.[18]

Sodium acetate is significantly more expensive than other common anti-icing products. Some agencies use it in specific small areas, such as elevated ramps or parking lots. It can be applied with the same equipment as ammonium-based products, so often agencies will approach winter weather using a combination of the two ice melters.[17]

2.1.6 *MAGNESIUM CHLORIDE*

Many agencies that have used sodium chloride or calcium chloride in the past have now begun considering magnesium chloride ($MgCl_2$). Its lowest effective temperature is around -15 degrees Fahrenheit, so it is stronger than sodium chloride but not as strong as calcium chloride.[7] It is similar to calcium chloride in that it is exothermic and its hygroscopic pellets initiate melting. It is 53% water by weight, which means more must be applied to deliver ice melting capacity equal to calcium chloride, but it works almost immediately once applied.[19]

Magnesium chloride is less than half as harmful to concrete as calcium chloride.[20] It can still cause damage pavements, though. It does not directly attack the concrete like other ice-melting products. Instead, it increases the amount of water that seeps into pores in the concrete and creates damage through freeze-induced expansion. Concrete that is less than one year old is most at risk for this type of damage. Magnesium chloride does not harm asphalt.[21]

Magnesium chloride is often mixed with sodium chloride or sand and applied to roadways. It can be easily incorporated into most existing winter maintenance infrastructure. There are many commercial blends that contain magnesium chloride, including some that were tested in Kentucky's research.

2.1.7 *AGRICULTURAL-BASED PRODUCTS*

Because so many of the current practices are harmful to the environment, some manufacturers have begun introducing organic materials in order to balance the risk. These materials often come from agricultural processes (referred to as "agro-based" or "bio-based") and may pose less of an environmental threat.[22]

Most agro-based products contain sugar in some form. Many agricultural processes produce sugars, sugar alcohols, and/or carbohydrates as byproducts. Popular sugar-based ice melters that are currently on the market include beet juice, corn syrup, vodka byproduct, grape extract, and glycerin.[23] Sugars depress the freezing point of water further than chloride salt alone, resulting in a longer working time, lower application rates, and reduced corrosion.[24] Additionally, sugar products are usually sticky, helping to ensure that salt products cling to the surface and stay on the road, thereby reducing runoff that can damage plants and aquatic environments.[25] Sugars are fully biodegradable and are generally considered safe for aquatic life. However, long-term use of sugars could attract more bacteria to the water over time.[26]

Agro-based ice melters are highly dependent on their location, availability, and the current agricultural production. For example, beets are commonly grown in the Midwest United States; areas further away from beet production may pay a premium for transport and storage. Grape-growing is most common on the west coast of the United States, so it would be reasonable to use grape extract in an ice melter in that region.

2.1.8 *CORN STARCH*

Corn starch was first introduced as an ice-melter in 1998. The benefit of using corn starch as an ice-melting product is largely physical. Corn starch increases the viscosity of fluids as they are sprayed on the highway and forms a water gel structure on the road. The gel provides a "platform" in the top portion of the pavement, helping retain salt or brine near the surface of the roadway for an extra two to four hours. This reduces the need for subsequent salt treatments.[27] There is some evidence that suggests the corn starch may degrade into sugar alcohols that can reduce the freezing point of ice further than salts alone.[24] An added benefit of corn starch additives is that they have no effect on the environment; they can be used near sensitive environmental areas and near water.[28]

2.2 SURVEY OF OTHER STATES

In order to better understand which public agencies are using blended liquid products for anti-icing, KTC researchers prepared a survey to assess current practices across the country. The survey was distributed electronically to all members of a listserv group established by the AASHTO Winter Maintenance Technical Services Program (SICOP). SICOP was established in 1993 as a pooled fund study by a group of winter maintenance professionals. The purpose of the group then was to study international winter maintenance practices and then quickly moved into a technology transfer mechanism for agencies interested in improving winter maintenance through technology, equipment and best practices. SICOP established the listserv in 2001 and the email communication method has been in regular use ever since. There are approximately 600 subscribers on the listserv representing metropolitans, counties, state DOTs, and vendors. The survey generated twelve usable agency responses, which are summarized in the following paragraphs. There were additional responses; however, those agencies indicated that they do not routinely blend products for anti-icing or pre-wetting and so were not included in the information in this summary.

The survey included eight questions. Those questions included which products the agency uses for anti-icing and for blended treatments whether the agency bought ingredients and mixed the chemicals on site or purchased a pre-mixed additive and incorporated into the salt brine. Additional questions solicited information on how the agency selected the product(s) being used, including whether or not any research had been completed, the cost of the product(s), and the agency experience with the product(s).

The first question asked agencies to provide all products routinely used for anti-icing or prewetting rock salt. Of the twelve respondents, six of them use magnesium chloride, five use calcium chloride, three use beet juice products, three use potassium acetate, one uses calcium magnesium acetate (CMA), and one has used potato byproduct. In addition, five agencies indicated that they use one or more commercially prepared liquid additives. Those were Agua Salina (chloride blend), Clear Lane ($MgCl_2$), Shield GLT (corrosion inhibitor), FreezGard ($MgCl_2$ and corrosion inhibitor), Meltdown Inhibited ($MgCl_2$ and corrosion inhibitor), ThawRox ($MgCl_2$ and carbohydrate), Caliber (corn product), Ice Ban (corn starch), GeoMelt (beet juice), Beet Heet (beet juice), and Magic Minus Zero (carbohydrate).

The second question on the survey asked if the agency blends products for anti-icing or prewetting. Agencies that indicated 'no' in the response or mentioned instances where one of the chemicals listed was used in a 100% solution were noted but not pursued since the focus of this study is on blended products.

For the responses that indicated blended usage, the subsequent questions asked the agency to identify the specific product used. In most cases, the chemical additives are typically blended with 23.3% solution salt brine, though they are occasionally mixed with calcium chloride. Magnesium chloride is blended at 5-20% solution with the remaining 80-85% of the solution salt brine. Similarly, calcium chloride is blended with brine at 5-20% solution. Beet juice is blended at 10 or 20% solution with brine or a brine and calcium chloride mix. Potato byproduct is blended at 5% with 95% brine solution or calcium chloride. Magic Minus Zero and Shield GLT are both blended at 5% solution with 95% brine.

The survey contained two questions regarding the agency's testing and selection process. Agencies said they made their choices based on two main reasons: 1) the desire to improve the effectiveness of brine at lower temperatures, including ensuring the brine did not freeze in the storage or distribution tanks, and 2) the desire to inhibit the corrosive nature of brine or other ice-melting products. Seven agencies conducted field testing and/or sales visits followed by field trials. Two agencies rely on their contract partners to select appropriate product based on price and effectiveness, and do not track performance of products. Only one agency had conducted a formal research project on the products. From their research, they decided to use magnesium chloride to treat small areas and hardpack snow but still mostly relied on brine. Many states referenced the Pacific Northwest Snowfighters (PNS) and their catalog of approved winter maintenance products, the Qualified Products List (QPL). Clear Roads assumed control of the QPL in 2018, but this survey was sent out in 2017 when it was still under PNS.

The final question of the survey asked for any cost information the agency could share regarding the products they use. Costs were provided in various forms by the respondents and they varied significantly. In general, the cost to produce brine ranges from $0.08 to $0.45 per gallon, as provided by four agencies. The cost of the added ingredients ranges from $0.26 to $2.48 per gallon. Once blended, for the agencies where calculations could be determined, the blended mixture cost from $0.12 to $0.34 per gallon. The costs provided covered 3 prices for magnesium chloride, two prices for calcium chloride, one price for potassium acetate, one price for blended brine and beet juice, and one price for potato byproduct.

The review of survey responses assisted the study advisory committee's decision on the products to pursue for laboratory testing. The final choices are summarized in Section 3.1.

2.3 TESTING METHODS

While there are a wide variety of anti-icing and de-icing products in use, many agencies were not able to provide clear reasoning for their choices. They were unsure of the performance of their choice compared to others. This is not surprising: the products are very difficult to test and form conclusions about their potential use. There is no uniform testing procedure in place that allows agencies to make informed decisions about their anti-icing and de-icing products. In fact, there is a remarkably small amount of literature regarding potential testing methodologies. Testing methods vary, as do the objectives. Some of the tests have been performed in a lab, others have been performed in the field, and other methods are strictly theoretical. In some cases, researchers performed tests on proprietor blends and had to keep some information undisclosed, which makes it nearly impossible for other researchers to repeat their experiments or modify them appropriately. However, the research on prior testing and suggested methods informed KTC's ability to develop their own testing protocol. The rest of this section describes the requirements that should be met when testing a new material.

First, it is important to ensure that all ice melters have been evaluated and approved by the appropriate entity. In this case, Clear Roads approved all the ice melters that KYTC was interested in testing. Clear Roads is a national research consortium focused on rigorous testing of winter maintenance materials, equipment, and methods for use by highway maintenance crews. Their list of approved ice melters is the Qualified Products List (QPL). Products selected for inclusion on the QPL must pass a series of tests for friction, corrosion, and chemical and toxicological properties, and meet environmental and health standards. Liquid anti-icers are subjected to three tests: concentration percentage of active ingredient, corrosion rate, and percent total settleable solids and percent solids passing a no. 10 sieve. It is important to note that inclusion on the QPL is based on composition and safety standards rather than performance as an ice-melter.[29]

Next, an agency should decide what type of ice melting capability they are interested in testing. Ice melters can be evaluated in terms of their melting ability, their ice undercutting ability, or their ice penetration ability. Because KYTC was interested specifically in anti-icing agents, the most important trait was a product's ice undercutting ability, or its ability to disrupt or prevent the bond between ice and pavement. The Strategic Highway Research Program (SHRP) provides guidance for various ice melting tests in its 1992 document: Handbook of Test Methods for Evaluating Chemical Deicers. The recommended ice undercutting test measures the area of the brine film formed between a layer of ice and a substrate material. Various substrates can be used, but the substrate of choice for deicer evaluation in the lab is concrete-based because of its smooth surface. In the recommended test, a 1/8-inch thick layer of ice is frozen slowly from the bottom upward. This mimics the way ice forms on cold pavement and it also ensures the ice is clear so melting measurements can be accurate. Then, small cavities are created in the ice, into which weighed samples of dyed anti-icer are inserted. The dyed anti-icer spreads out underneath the ice in a radial manner. Photographs taken at time intervals track measurements of the melted area. The SHRP Handbook acknowledges that the recommended test method produces very symmetrical melted areas which may be considerably smaller than undercut areas obtained with less strongly bonded or less perfect ice formed under natural conditions.[30] Since the SHRP Handbook tests had not been performed at the time of publishing and were only theoretical, they lacked some of the troubleshooting measures that may have come up during testing. Nevertheless, the methodology served as an excellent starting point for KTC to develop and refine their own lab testing methodology.

KTC researchers also examined the work of several other agencies that had performed ice melting tests, including some tests that resembled the SHRP Handbook methodology and other tests that were unrelated. The predominant takeaway from others' research was that testing deicers in the laboratory is an excellent way to compare the relative performance of deicers, but the exact values from laboratory tests generally do not correlate directly with actual field performance.[4] Still, the products' relative performance tends to remain the same in the field as it was measured in the laboratory. For KYTC, laboratory testing is adequate for the purpose of comparing deicer products and determining the best performer.

Previous ice melting research has experimented with controlling different variables within laboratory testing. During the most effective laboratory tests, the parameters that were controlled were: air temperature, pavement temperature, relative humidity, pavement type, and uniform snow/ice. Ideally, traffic and plowing simulations should also be included during testing, but that is not always possible. The environment has more of an effect on anti-icing performance than traffic does. Therefore, controlling as many environmental parameters as possible is more important than simulating traffic and plowing.[4]

According to a 2010 Clear Roads research study, SHRP's ice undercutting test methodology is the most representative of actual field performance of deicers, while it also maintains several benefits of a standard laboratory test.[4] In fact, two concurrent 1992 experiments tested the connection between ice undercutting and disbondment (such as shoveling or plowing) and concluded that in most cases, the percentage of ice removed from the pavement is equal to the percentage of undercut area.[30,31] Thus, SHRP's simple ice undercutting test provides enough indication of the disbondment characteristics of anti-icers.

In 2009, Shi et al. performed SHRP's ice undercutting test for solid and liquid products. They took digital photos and then used Adobe Photoshop to measure the undercut area. Exact measurements were calculated by counting the number of pixels of dyed area. They observed that most ice melting products did not initiate undercutting until about 20 minutes into the test. This study suggested that 32 degrees was the optimal temperature for the ice undercutting test. It can be inferred that 32 degrees is cold enough to mimic the real environment but warm enough to allow adequate melting. They found that the SHRP methodology was more useful for liquid deicers than solid deicers. The solid deicers often separated from the dye; the dye would spread across the surface of the substrate without the deicer, giving the appearance of undercutting without any true melting.[32]

The same study also evaluated the corrosion effects of various ice melting products. Their conclusions prove that corrosion-inhibited anti-icers do indeed reduce the amount of damage to mild steel. Continuing to use uninhibited chloride-based ice melters on steel-reinforced concrete may have severely negative implications over time. Additionally, this research attempted to bridge the gap between laboratory tests and field tests. Research regarding ice melters on the road indicated that the chemical additives react with cement hydrates and form new products in the pores and cracks. According to thermodynamic laboratory tests, some new reaction products include oxychloride crystals, which can produce strong kinetic reactions. Thus, chloride-based ice melters can instigate both physical and chemical damage to infrastructure.[32]

Other research has endeavored to test ice melters in a field setting as well. Field testing is even less regulated than laboratory testing and, like laboratory tests, only provides reliable information about the relative performance of ice melters rather than absolute standards. It is also significantly harder to control environmental variables in a field setting. The Minnesota DOT and Clear Roads have developed a short guide about how to approach field testing. They recommend a simple garage test that is entirely observation-based, a single roadway test to observe how traffic impacts deicer performance, and/or a side-by-side test to evaluate a new product next to a control. The guide emphasizes the importance of controlling all parameters other than the ice melting products and does not recommend field testing if environmental variables often change.[33] In general, research suggests that, while neither laboratory or field tests will provide a complete picture of an ice melter's performance, laboratory tests are valuable in that they may provide some guidance in developing and interpreting field tests.[4]

CHAPTER 3. METHODOLOGY

3.1 PRODUCTS OF INTEREST TO KENTUCKY

Performing the literature review and agency survey introduced the research team to a variety of different anti-icing and deicing products. After consulting with Kentucky Transportation Cabinet officials, five products were selected for testing. The products comprised an assortment of commercial blends that are readily available in the state or that have been recommended by other agencies. With the hope of finding environmentally-friendly options, the team also chose some bio-based products. The products that were chosen were:

- BioMelt AG64, a sugar alcohol blend made with beet byproducts
- FreezGard Cl Plus, a magnesium chloride product that contains a sulfate corrosion inhibitor
- Ice-B'Gone Magic, a 50/50 mix of distillers' byproduct and magnesium chloride
- Ice Ban 305, a mix of corn starch and magnesium chloride
- Calcium chloride, KYTC's current practice

3.1.1 *BIOMELT AG64*

BioMelt AG64 is a completely organic sugar alcohol blend made with beet byproducts. It is a dark, sticky liquid that can be applied to roads as an anti-icer or mixed with rock salt to form a deicer. Beet juice depresses the freezing point of water further than rock salt alone. Specifically, BioMelt is effective to -40 degrees Fahrenheit. Because BioMelt AG64 is sticky, it helps keep products on the road and reduces runoff waste; the manufacturer asserts that this can reduce anti-icer application rates by 30-50%, compared to typical chloride deicers.[34]

3.1.2 *FREEZGARD CL PLUS*

Magnesium chloride is a common base for deicers and anti-icers. One commercial product, FreezGard Cl Plus, contains 30% magnesium chloride as well as a sulfate additive. The sulfate additive acts as a corrosion inhibitor without lessening the melting capability of the magnesium chloride.[35] Sulfate inhibits corrosion by forming passive protective film layers and reducing galvanic currents between dissimilar metals.[36] This makes FreezGard Cl Plus safer for pavements and bridges. FreezGard Cl Plus has a working temperature of about 0 degrees Fahrenheit.[35]

3.1.3 *ICE-B'GONE MAGIC*

"Ice-B'Gone Magic" (referred to as IBG Magic or also known as Magic Minus Zero) is 50-60% magnesium chloride combined with 40-50% distiller's byproduct. The byproduct is a grain or sugar solution that is produced during the production of vodka and rum. These liquid byproducts are added to the salt or brine in specific proportions to significantly lower the working temperature of chloride salt. This allows a longer working time, lower application rates, and reduced corrosion. IBG Magic's freezing point is -45 degrees Fahrenheit; when it is used as a salt additive, the mixture's freezing point is -35 degrees Fahrenheit.[37]

3.1.4 *ICE BAN 305*

Corn starch acts as an organic inhibitor in several anti-icing blends. Ice Ban 305 (recently rebranded to Torch IB) is a corn starch-based anti-icing additive which also contains 25% magnesium chloride. Ice Ban is a clear, colorless liquid with a freezing point of -67 degrees Fahrenheit. The blend was originally introduced for use in sensitive environmental areas where significant reductions in phosphorus and nutrients are necessary to protect a fragile ecosystem. Initial application rates are similar to other anti-icers and deicers, but the corn starch helps the product stay on the road longer, thereby reducing the reapplication rate.[38]

3.1.5 *CALCIUM CHLORIDE*

Calcium chloride is the most common anti-icer in use in the United States; KYTC has used it for decades. Calcium chloride is fast-acting, efficient, and works in temperatures as low as -29 degrees Fahrenheit.[7] For KTC's laboratory experimentation, calcium chloride was used as a control to compare the innovative products to an existing baseline.

3.2 LABORATORY METHODOLOGY

The purpose of laboratory tests was to measure the ice undercutting ability of the five identified anti-icers. The anti-icers were not diluted with brine; this ensured that data would show the melting capabilities of the anti-icer itself. The laboratory test developed by KTC researchers was loosely based on the SHRP H205.6 test, which "tests the ability of a deicer to melt ice at the interface between a layer of ice and a pavement substrate."[30] The SHRP H205.6 testing methodology was published in 1992, but was only theoretical and had not actually been performed. KTC researchers adapted the SHRP testing methodology to fit within constraints of their laboratory's walk-in cold room, and added some modifications to increase effectiveness and troubleshoot problems that occurred during the early stages of testing.

The full laboratory test involves the following steps:

1. Mix and cure mortar mix substrate ("Quikrete").
   Use 4 pints of tap water to each 50 pound bag, mix according to directions.
   Mold consists of a plastic Rubbermaid tray 6"x9"x2" deep, lined with parchment paper. The bottom surface of mold becomes the top surface of testing substrate.
   Let cure for one full day before use.
2. Freeze ice on substrate using bottom-up technique:
   Create barrier using plastic form (3D printed) and latex caulk.
   (When creating barrier leave room for ruler to be placed on top of concrete next to barrier.)
   Freeze dry substrate at 14 degree Fahrenheit.

Contain pre-chilled, distilled, filtered water on surface of the substrate within the barrier to yield 1/8-inch thick layer.
Place a cold metal plate (14°F) underneath the pavement substrate.
Maintain the air temperature at 28 degrees while the water freezes.
Cover the water with plastic sheeting. This prevents dust from getting into the ice and keeps the surface a little warmer so that the bottom-up technique can be employed.
If it freezes too quickly and is cloudy or contains air bubbles, heat the top of the ice with a gentle indirect heat source so that the top half is water and the bottom half is ice, and then re-freeze. May repeat several times.
The ice must be completely uniform and clear before proceeding with the next steps.

3. Form cavities in ice using a warm aluminum rod and a syringe:
   Use aluminum rod with a nominal diameter of 5/32 inches (found at hardware store) and place rod in 100 milliliters water warmed to ~150 degrees Fahrenheit.
   Press warmed aluminum rod vertically into surface of ice, press with moderate pressure for 3 to 4 seconds. Can be extended or repeated as needed in order to ensure cavity extends all the way down to the pavement substrate.
   Use 5-milliliter plastic syringe with plastic tip (diameter 4.064mm) to extract melted water from cylindrical cavity.
   Create cavities in sets of five; each specimen should accommodate three sets of five cavities, with cavities about four centimeters apart.
4. Combine liquid additive and dye.
   Add liquid deicer to vial of dye (15-20 milligrams).
   Cool to test temperature or the lowest temperature at which the deicer remains a liquid.
   Gently agitate this combination regularly during testing to make sure the dye does not separate and that solids do not precipitate out of solution.
5. Place anti-icers within ice cavities.
   With a pipetting system, place a 30-microliter quantity of deicer in each of the five cavities.
   This step must be performed quickly and within the cold room.
6. Take pictures of the melting process.
   Set up tripod directly over substrate so that the camera has vertical straight-on view of the ice surface.
   Place ruler on the concrete substrate outside of the plastic barrier.
   Take pictures of the substrates at 0, 2, 4, 6, 8, 10, 15, 20 and 30 minutes.
   Do not move the camera or substrate during this process.

In this test, ice melting occurs in part by enlargement of the cavity, and in part by melting at the interface between ice and substrate. Both are captured by taking photos from above; the dyed area increases over time as the anti-icer works.

The tests are performed at 30 degrees Fahrenheit. This temperature was chosen in an effort to mimic Kentucky's winter weather: average low temperatures in January range from 23 to 28 degrees.[1] According to KYTC's snow and ice program, anti-icers are applied at between 20 and 35 degrees. 30 degrees was within this range but warm enough to still see significant, measurable melting. The relative ambient humidity for all tests was between 86% and 87%, which reflects the higher end of Kentucky's winter humidity levels since humidity is expected to be highest during winter precipitation.[1]

It is important to note that this test does not necessarily represent conditions that would exist under normal field application conditions. In practice, anti-icers would be applied before a snow event and therefore prevent a bond from forming between the pavement and the snow or ice. In a laboratory setting, however, ice must exist before melting can be measured. The laboratory test serves as a valuable tool to accurately estimate ice-undercutting ability, even though it occurs at a different point in the process than it would under actual winter weather conditions.

3.3 DATA PROCESSING

The product of the laboratory work was a collection of photos taken at regular intervals. Figure 3-1 shows an example of a photo taken to measure an anti-icer's undercutting ability. During testing, a ruler was placed next to the ice so that it was level with the surface of the substrate and within the frame of the photograph. Using the ruler as a conversion factor between length and number of pixels, one can determine the exact area of melted ice for each photo. This can be done via ImageJ, an image processing program designed for scientific images. Within Image J, a line was drawn between points on the ruler and that distance was defined to effectively create a scale for the image. Then, the image was converted to an RGB color image; this helps the user identify what colors are in the image. By manipulating saturation parameters, the Image J user can highlight the zones of the ice that were undercut by the dyed anti-icer, as shown in Figure 3-2. Then, that zone's number of pixels is converted to an area using the previously-established scale. Area outlines are drawn, as shown in Figure 3-3. The result of photo processing with Image J is a set of area measurements that represent the amount of ice that was undercut by the anti-icer used.

Figure 3-1: Example of photo taken during laboratory testing

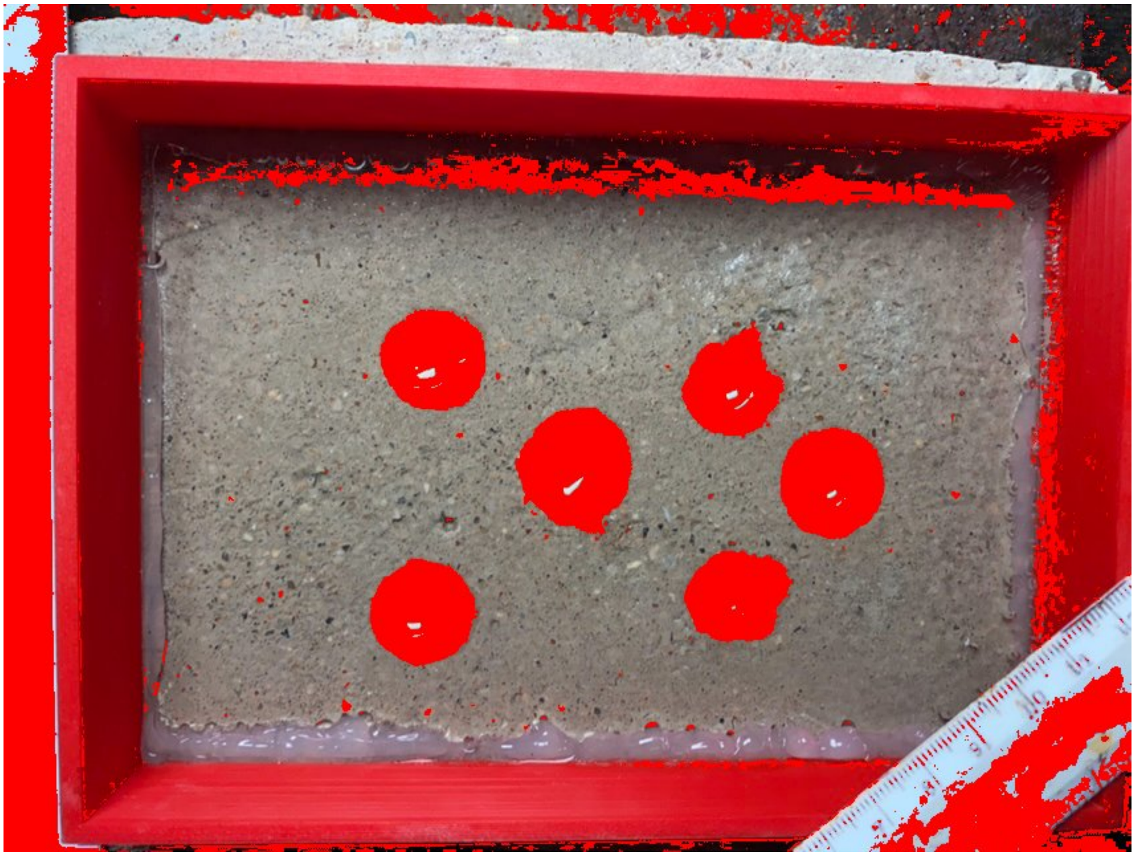

Figure 3-2: ImageJ color manipulation to identify undercut areas

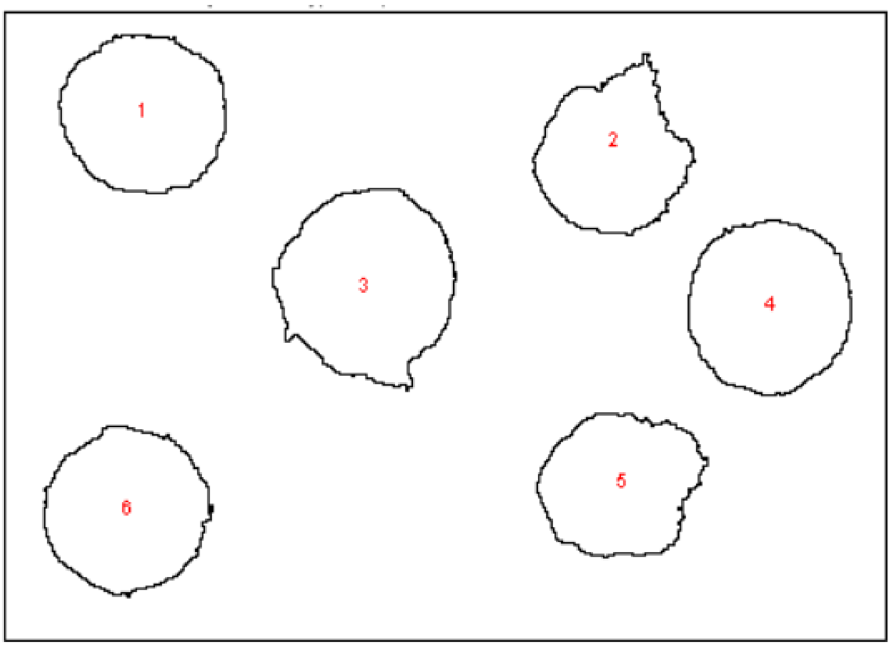

Figure 3-3: Undercut areas as identified by ImageJ

CHAPTER 4. RESULTS

4.1 UNDERCUTTING ABILITY

The main objective of the laboratory study was to determine the ice-undercutting ability of each anti-icer. The anti-icers were tested on their own, not mixed with brine. Over a period of thirty minutes, the anti-icers disrupted the bond between ice and pavement substrate, creating zones of measureable undercut areas. Measurements of the undercut areas were taken at designated intervals.

4.1.1 *AVERAGE UNDERCUT AREAS*

The undercut areas were compiled and averaged for each anti-icer, as shown in Table 4-1.

Table 4-1: Average undercut area of each application of anti-icing additive

		0 mins	2 mins	4 mins	6 mins	8 mins	10 mins	15 mins	20 mins	30 mins
Compounding undercut area (mm^2)	Ice Ban 305	26.8	67.0	99.4	125.8	139.7	155.7	177.5	197.7	215.7
	IBG Magic	26.4	69.1	88.9	115.8	132.5	147.0	176.7	190.1	217.7
	FreezGard Cl+	33.4	82.1	132.0	168.4	200.4	224.6	260.8	289.9	318.2
	BioMelt AG64	18.9	45.1	76.3	99.9	116.2	131.3	156.4	183.5	201.0
	Calcium	26.7	48.5	79.5	100.8	119.2	133.7	159.4	177.9	201.6

A graph of these results is provided in Figure 4-1.

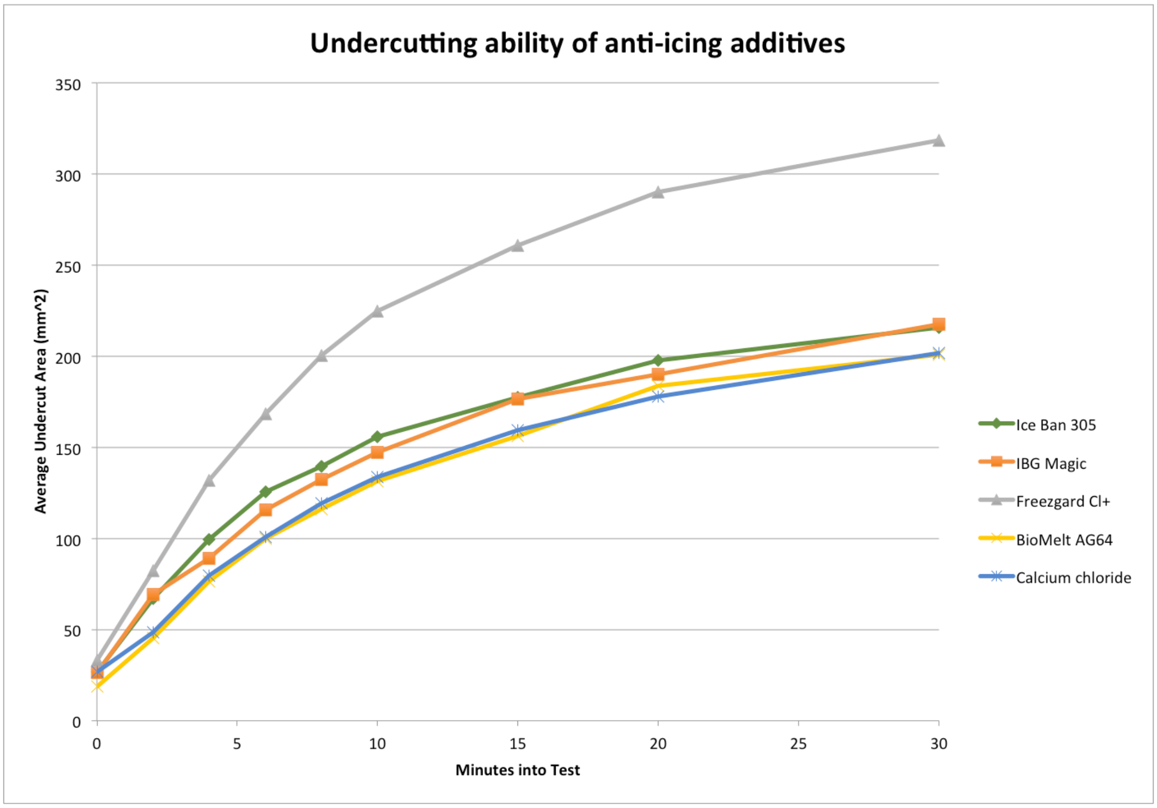

Figure 4-1: Average undercut areas of anti-icing additives during 30-minute test

Of the undiluted anti-icers, FreezGard Cl Plus performed the best. Each application undercut an average area of 318.22 square millimeters. FreezGard Cl Plus started disrupting the bond between ice and substrate within the first two minutes and continued to spread out over the substrate at a fairly steady rate. By the end of the thirty-minute test, it had undercut an area about one and a half times as large as the next best performer.

IBG Magic and Ice Ban 305 were second in terms of performance, and they performed equally well, creating average undercut areas of 217.69 mm^2 and 215.70 mm^2, respectively. When the tests ended at thirty minutes, IBG Magic had undercut more area; however, it is not possible to determine which would have performed better over a longer period of time.

Calcium chloride and BioMelt AG64 performed comparatively. Calcium chloride undercut a total average area of 201.64 mm^2. KYTC's current anti-icer, calcium chloride, is only about 60% as effective as FreezGard Cl Plus. BioMelt AG 64 undercut a total average area of 200.99 mm^2. BioMelt AG64 had a lower starting point than all other test subjects, possibly because its viscosity is higher and it was not able to immediately start spreading out the way the other liquids did.

4.1.2 *UNDERCUTTING WITH STANDARD DEVIATION*

A total of 1495 data points were collected across several trials of the five products tested. Each product's data points had varying degrees of precision. Precision was measured by standard deviation of each population, meaning there was a unique standard deviation for each time increment for each product. The standard deviations are compiled in Table 4-2.

Table 4-2: Standard deviation from the average values

		0 mins	2 mins	4 mins	6 mins	8 mins	10 mins	15 mins	20 mins	30 mins
Standard deviation from average (mm^2)	Ice Ban 305	9.1	14.4	12.1	15.0	19.0	20.7	25.0	27.0	33.7
	IBG Magic	6.3	19.0	27.4	33.7	41.9	46.3	54.3	61.1	75.8
	FreezGard Cl+	12.3	23.9	26.9	33.1	33.6	38.3	46.6	51.3	58.8
	BioMelt AG64	6.1	14.0	17.5	23.8	29.7	39.7	54.3	71.6	80.0
	Calcium chloride	5.6	15.6	26.3	33.9	42.5	46.4	59.4	66.7	77.3

As the table shows, Ice Ban 305 usually had the smallest standard deviation across all its measurements. This means that the undercut area of each application of Ice Ban was consistent and relatively close to the same value for all measurements within each time increment. When averaged, the standard deviation of the data points for Ice Ban 305 was about 17% of the undercut area. It was the most precise of all five additives. FreezGard Cl Plus was the second most precise additive; its average standard deviation was about 22% of each undercut area. The other three additives were less precise. When the standard deviation values of IBG Magic, BioMelt AG64, and calcium chloride were compared with their average undercut areas, the ratios were 30%, 31%, and 34%, respectively. It is also interesting to note that, while all five products' standard deviation values increased with time, the growth for Ice Ban 305 was more gradual compared to the others.

In Figure 4-2, the graph for undercutting area has been supplemented with bars to represent standard deviation of each population.

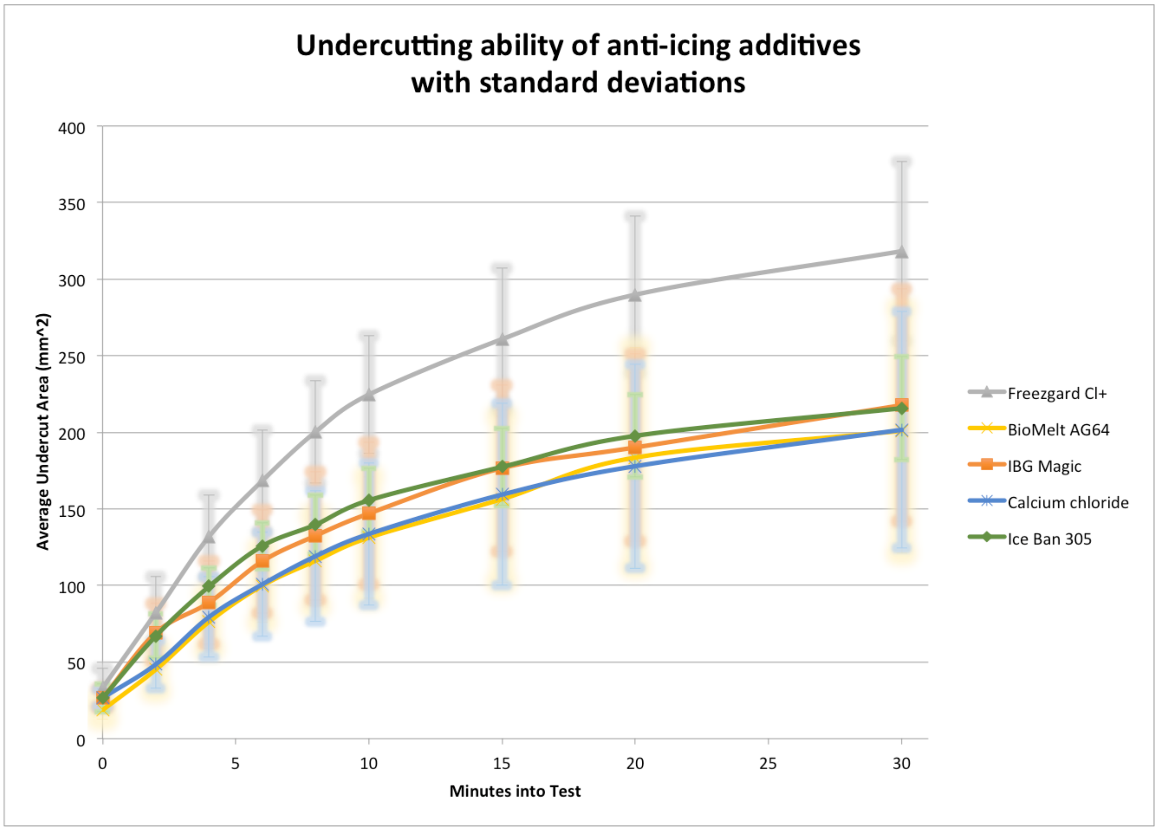

Figure 4-2: Average undercut area of each additive with standard deviation bars

4.1.3 *UNDERCUTTING WHEN DILUTED*

Anti-icing additives are applied with brine. Additive distributors provide a recommended dilution for each product, usually ranging between 5% and 30%. In the case of this study's additives, calcium chloride and Ice Ban 305 should be applied at 5%, FreezGard Cl Plus should be applied at 10%, IBG Magic should be applied at 15%, and BioMelt AG64 should be applied at 20%.

Laboratory tests were performed at full strength, not at the recommended dilutions. Still, an estimation of the performance of the diluted additives may be inferred by applying the dilution percentage to the values from the full-strength tests. When those dilutions are applied, the data creates the graph shown in Figure 4-3.

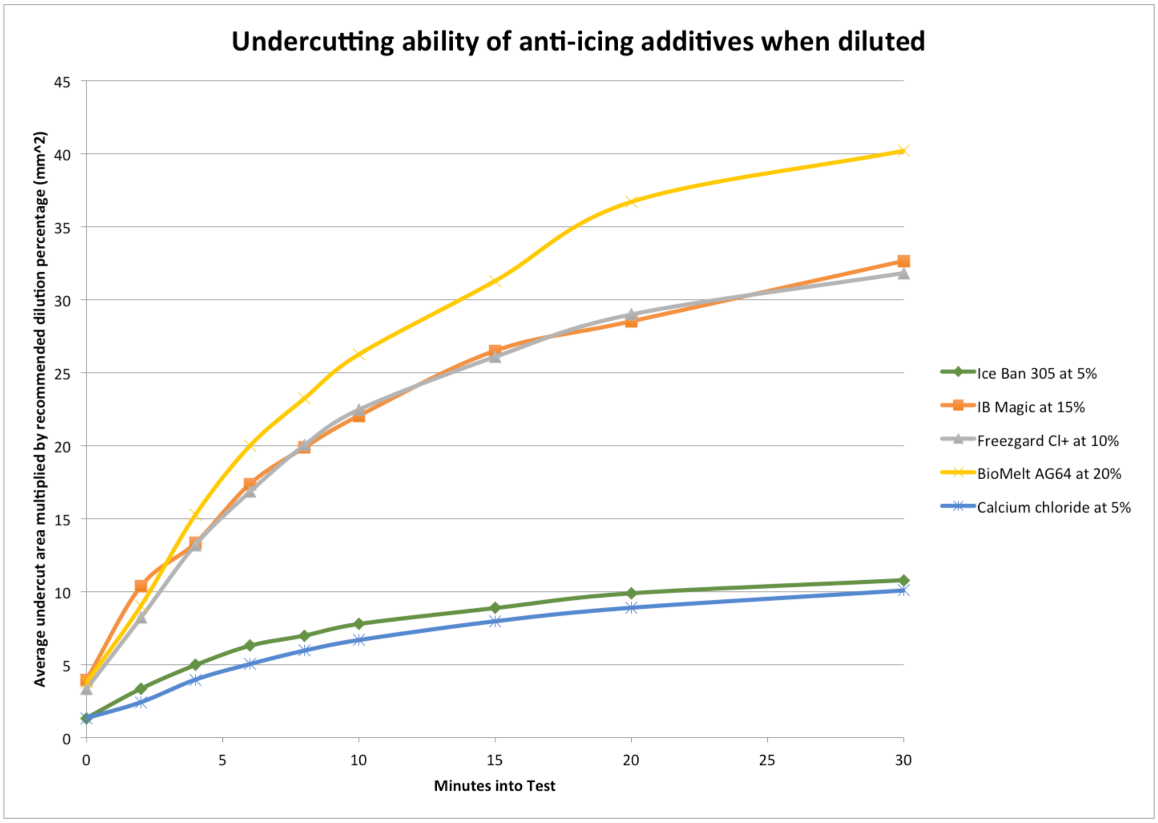

Figure 4-3: Calculated undercut areas when dilutions are applied

When diluted at the recommended percentages, BioMelt AG64 performs best. This is perhaps not surprising because its percentage in solution (20%) is the highest of all five products. FreezGard Cl Plus at 10% and IBG Magic at 15% perform next best. Their performance when diluted is about 80% of BioMelt AG64's performance. IceBan 305 and calcium chloride, both in 5% solution, perform similarly to each other and very unfavorably compared to the others.

KYTC indicated that the dilution percentage of calcium chloride could be increase to 15% without inhibiting application equipment. If 15% is applied to calcium chloride instead of 5%, the undercutting curve rises to just below those of IBG Magic and FreezGard Cl Plus.

It is important to note that a product's performance when diluted is not necessarily directly correlated to its value in the field. Other factors such as price and longevity will ultimately influence the overall value of a product. More information about the dilution of these products and how they influence cost is provided in Section 4.2.

4.1.4 *UNDERCUTTING RATE*

To understand how quickly these anti-icing additives take effect, the undercutting rate was evaluated. This metric focuses on how much area was undercut within each time increment, rather than the compounding total undercut area presented in Figure 4. It is valuable to analyze the rate because some storms or agencies might require fast-acting anti-icers, while others might prefer those that work steadily over a longer period of time. The undercutting rate is presented in Figure 4-4.

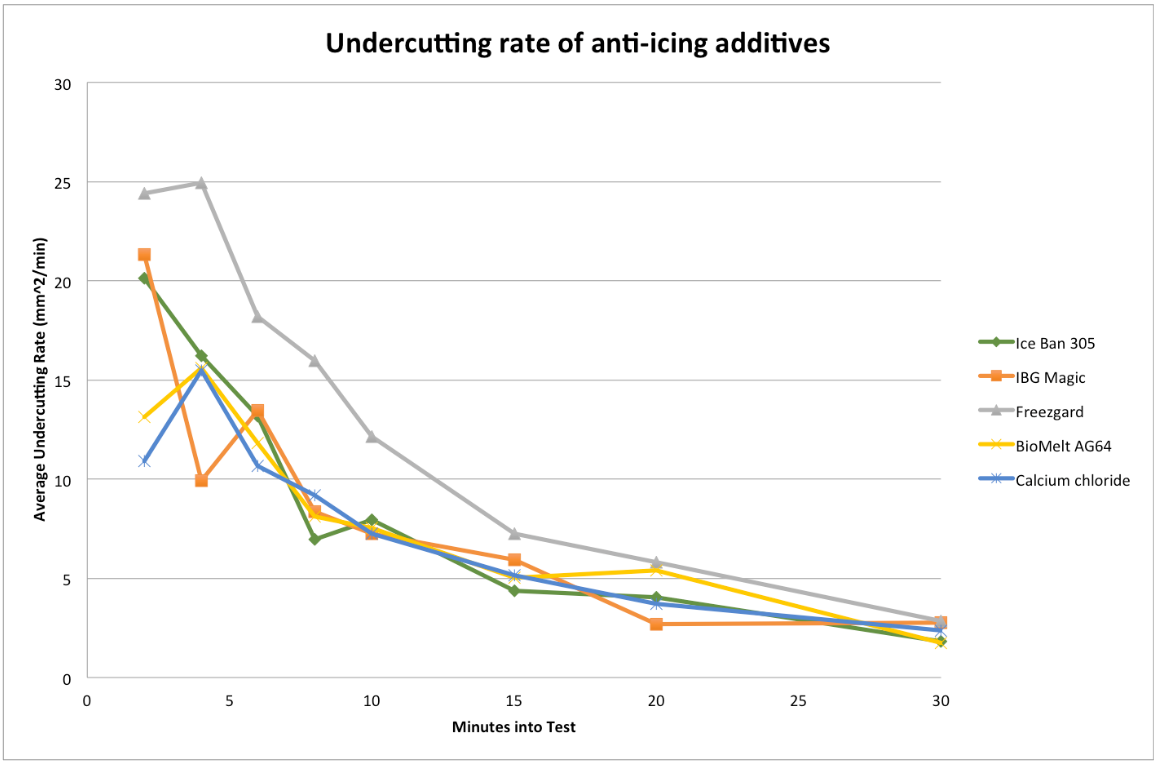

Figure 4-4: Undercutting rate of each liquid additive

FreezGard Cl Plus, which undercut the largest total area, also performed well in this analysis. Its initial undercutting rate was just under 25 mm^2 per minute. In contrast, the calcium chloride control had an initial undercutting rate of about 11 mm^2 per minute. IBG Magic performed very strongly upon application, but then its undercutting rate significantly slowed within the first two minutes. All five products have an undercutting rate that slows down over time. By the end of the thirty-minute test, the undercutting rates of all five additives were very similar, about 3 mm^2 per minute.

4.2 COST

Since the cost of a product is an important consideration to the state, the anti-icing blends were evaluated for their price as well as for performance. The cost of commercial products can vary depending on the location where it is used and the amount of product required. The following prices were determined by using Frankfort, KY as the delivery point and by requesting a minimum of 4,500 gallons per order (which is a typical minimum).

- Calcium Chloride: $0.95/gallon
- FreezGard Cl Plus: $1.29/gallon
- Ice Ban 305: $1.81/gallon
- BioMelt AG64: $2.10/gallon
- IBG Magic: $3.00/gallon

Costs should also be evaluated in terms of the distributor-recommended dilution. These anti-icing materials are usually not used by themselves, but as additives to brine. The cost of brine is $0.12 per gallon. Table 4-3 summarizes the additive costs along with the distributor-recommended dilutions and associated cost of the mixture. In the last column, a cost per lane mile was calculated using KYTC's standard practice of 45 gallons per lane mile.

Table 4-3: Cost of anti-icing additives

Anti-icer	Cost per gallon	Recommended dilution	Cost per gallon when diluted with brine	Cost per lane mile
Calcium Chloride	$0.95	5%	$0.16	$7.27
FreezGard Cl+	$1.29	10%	$0.24	$10.67
Ice Ban 305	$1.81	5%	$0.20	$9.20
BioMelt AG64	$2.10	20%	$0.52	$23.22
IBG Magic	$3.00	15%	$0.55	$24.84

Calcium chloride solution, the current product, is the most cost-effective option for both cost per gallon or cost per lane mile. FreezGard Cl Plus and Ice Ban 305 are the next most economical additives. Per lane mile, FreezGard Cl Plus is about 1.5 times the cost of calcium chloride, and Ice Ban 305 is about 1.25 the cost of calcium chloride. When comparing FreezGard Cl Plus and Ice Ban 305 to each other, it's important to note that the price per gallon of FreezGard Cl Plus is less than Ice Ban 305, but the distributor-recommended concentration is stronger; therefore the price per mile of FreezGard Cl Plus is slightly higher than that of Ice Ban 305. BioMelt AG64 and IBG Magic have high gallon prices *and* their concentration in solution is higher, so they ultimately have the highest cost per lane mile.

This cost analysis concludes that FreezGard Cl Plus and Ice Ban 305, two top performers in terms of melting, could both be adequate substitutions for calcium chloride without exorbitantly raising the cost of winter maintenance operations.

4.3 APPLICATION AND STORAGE

A central factor in choosing an anti-icer is its ease of application and efficiency of storage. When making decisions related to storage of ice melters, it can be helpful to consider the concept of eutectic curves that was introduced in Section 1.3. Eutectic curves indicate the temperatures and concentrations that are noteworthy for storage concerns, including the liquid's freezing temperature and the temperature at which solids may begin to precipitate out of solution. The Clear Roads QPL tests include a test for settleable solids; any product on its approved list must contain less than 1% settleable solids when stored for one week. The temperature at which a product can be stored with no more than 1% of solids precipitating out of solution is called the "typical cold storage temperature". Agencies should consider this typical cold storage temperature and how it corresponds with the existing storage arrangement.[39]

In Kentucky, salt, brine, and calcium chloride are held at KYTC district and county highway maintenance facilities. Each site has barns with the capacity for one million gallons of calcium chloride solution and one million gallons of salt brine. The tanks that hold the material are made of carbon steel with an epoxy-based interior coating and a durable, high-quality coating on the exterior. All four anti-icing alternatives can be used with existing equipment. Important notes regarding their use are summarized in the following paragraphs.

FreezGard Cl Plus is stable under normal conditions. It can be stored in the usual facilities, but it needs to be agitated regularly. At temperatures under zero degrees Fahrenheit, solids may start to precipitate out of solution. (This occurs in calcium chloride as well, but at a higher temperature of about 32 degrees Fahrenheit.) Application equipment should be rinsed daily with water to prevent buildup of solids. Aluminum storage tanks or hauling equipment should not be grounded. Agencies should take care to avoid contact between FreezGard Cl Plus and acids or strong oxidizing agents. Over-application of FreezGard Cl Plus results in slippery surfaces, so care should be taken to apply it in the correct amounts.[40]

IBG Magic is similar to FreezGard Cl Plus in that over-application can result in extremely slippery surfaces. IBG Magic is somewhat corrosive and will attack aluminum, brass, and some soft metals. Contact with strong oxidizers should be avoided.[37]

Ice Ban 305 is stable and nonreactive. According to its Safety Data Sheet, there are no conditions to avoid other than excessive moisture, which is a typical precaution for most ice melting products. Periodic recirculation is suggested during long-term storage.[38]

BioMelt AG64 is stable and unreactive. There may be minor corrosion when it comes in contact with light metals. BioMelt AG64 has a 100% shelf life, making it economical over time.[41]

4.4 ENVIRONMENTAL EFFECTS

The research team also evaluated the impact that these anti-icers may have on their environment. Environmental impacts can be discussed in terms of the effect on pavements and the effect on biosystems.

Three of the four novel products that were tested (FreezGard Cl Plus, Ice Ban 305, and IBG Magic) contain magnesium chloride. In general, magnesium chloride is less corrosive than calcium chloride and therefore less harmful on pavements.[7] However, it can increase the amount of water that seeps into the concrete's pores and create damage through freeze-thaw expansion. Mostly, this is only a hazard for pavements that are less than one year old.[21] In FreezGard Cl Plus, there is an additional corrosion inhibitor that reduces this risk even more. Ice Ban 305 contains corn starch, which may slow the rate of corrosion. The fourth novel product, BioMelt AG64, does not contain any chlorides. It poses no threat at all to pavements.

In terms of biological environmental impact, the five anti-icers present varying degrees of risk. Most importantly, none of these are considered hazardous to the environment or toxic to wildlife in the amounts they are meant to be applied. But, risks may be present over a long period of time as chemicals disperse and enter waterways or seep into groundwater. Of the five anti-icers that were tested, calcium chloride is the most harmful. Calcium chloride has a defoliating effect on trees and other plants.[42] If it leaches into waterways, it reduces the water's available oxygen levels which can pose a threat to aquatic life.[7] FreezGard Cl Plus is considered a more environmentally safe substitute, at least within the realm of chloride-based additives. The product itself and the process used to harvest the minerals are more environmentally friendly than calcium chloride.[40] Ice Ban 305, the corn starch anti-icer, is safe because it was initially developed for use in sensitive environmental areas where significant reductions in phosphorus and nutrients are necessary to protect a fragile ecosystem.[38] IBG Magic is designated by the EPA as a DfE (Design for Environment) product. It received this designation because, compared to many other anti-icers, it is less harmful to plants and aquatic life.[37] BioMelt AG64 is considered good for the environment because it does not contain chlorides and its sticky texture helps reduce runoff. However, if large quantities of it enter bodies of water, the high amounts of sugar can cause increased levels of bacteria.[25]

It is difficult to quantify the exact environmental impact and risks of using these commercial products, but researchers can conclude that any one of the four novel anti-icing blends has certain advantages over calcium chloride. Overall, the best way to manage environmental impact is to minimize the amount of road salt used. Adding a liquid anti-icer to the snow and ice maintenance program will support this objective because it is far more efficient to prevent the ice-pavement bond than it is to remove it after it has formed.[7]

CHAPTER 5. CONCLUSION

5.1 PRIORITY RANKING TABLE

The research that has been detailed in the previous chapters can be summarized with a priority ranking table, as shown in Table 5-1. The ranking table includes performance, cost, ease of use, infrastructure impact, and environmental impact. Each metric was weighted based on input from KYTC and given a score. Each metric is scored out of ten; higher scores are better and lower scores are worse.

Table 5-1: Priority ranking table for five anti-icing additives

Metric	Weight	BioMelt AG64	FreezGard Cl Plus	Ice-B'Gone Magic	Ice Ban 305	Calcium chloride
Performance	10	6.3	10	6.8	6.8	6.3
Cost	6	3.1	6.8	2.9	7.9	10
Ease of use	3	7	7	7	7	10
Infrastructure impact	2	10	6	4	8	1
Environmental impact	1	10	4	6	8	1
Total Score		132.6	177.8	120.4	160.4	156.0

KYTC's most important priority is performance, so that metric is weighted most heavily. A strong performer will maximize efficiency and minimize any drawbacks associated with its use. Performance scores are directly correlated with ice undercutting ability, as shown in Table 4-1 and Figure 4-1. The strongest performer received a score of 10 and each subsequent product was scored as a percentage of its undercut area compared to the undercut area of the strongest performer.

Cost is the next most important parameter. For this ranking table, cost was evaluated based on the cost per lane mile at the distributor-recommended solution. Again, cost scores are evaluated as a direct function of the actual costs, with calcium chloride receiving a score of 10 because it is the cheapest and all subsequent cost scores calculated as a percentage comparison.

Ease of use represents the ability of the agency to incorporate a new product into its existing application and storage equipment. Calcium chloride earns the full ten points because it is already there, but the other four products will all work fairly easily with the existing equipment and therefore their scores are all the same.

Infrastructure impact refers to the damage that a product may inflict on concrete, asphalt, and bridges. This metric was not tested in this research, but conclusions were drawn based on literature review and product safety data sheets. Most importantly, chloride based deicers will be most harmful to infrastructure and therefore receive low scores. Within that category, calcium chloride has been shown to be more harmful to pavements than magnesium chloride, so scores are distributed accordingly. Chloride deicers with a corrosion inhibitor can be given a middle score. Agro-based deicers are harmless to infrastructure and therefore receive the highest score.

Lastly, the environmental impacts are least important to KYTC because none of the products are considered especially hazardous. The environmental impacts were also the most difficult to objectively evaluate. For this metric, rankings were determined based on the information provided in section 4.4, with most emphasis given to how a product affects plants and waterways.

When summed, scores in the priority ranking table range from 120.4 to 177.8. FreezGard Cl Plus earns the highest score overall. It undercut the largest area in the laboratory tests, its cost is not significantly higher than KYTC's current practice, and its impacts on infrastructure and environment are minimal. Ice Ban 305 received the next highest score of 160.4. It performed fairly well in the laboratory tests and its cost is barely higher than KYTC's current practice. It is considered quite safe for infrastructure and the environment. Calcium chloride received the third highest score, 156.0. The main benefit of calcium chloride is based in its use as the current anti-icer. It is very cost-effective and no additional effort is needed to continue using calcium chloride. However, calcium chloride is detrimental to both pavements and biosystems, so it received very low scores in the last two categories. BioMelt AG64 and Ice-B'Gone Magic both received low overall scores, mostly because of their exceptionally high costs. Both have redeeming qualities, though: BioMelt AG64 is environmentally friendly and IBG Magic performed as well as Ice Ban 305 in laboratory tests.

While the development and specifics of this table may be unique to each agency, it can be a useful starting point to determine what factors are important when making decisions about ice melting products.

5.2 RECOMMENDATIONS

The current practice of using calcium chloride mixed with brine is functional and remains the most cost-effective option. Calcium chloride is fast-acting and works in temperatures as low as -25 degrees Fahrenheit. The research team also recommends FreezGard Cl Plus or Ice Ban 305 as potential substitutes for calcium chloride. FreezGard Cl Plus is 1.6 times as effective as calcium chloride at 1.5 times the cost. It contains 30% magnesium chloride and a sulfate additive that acts as a corrosion inhibitor. Its working temperature is about zero degrees Fahrenheit, which is well below Kentucky's average low temperature in winter. Ice Ban is 1.1 times as effective as calcium chloride and 1.25 times the cost. Its working temperature is -67 degrees Fahrenheit. Ice Ban 305 contains 25% magnesium chloride as well as corn starch. The corn starch thickens the brine solution, allowing it to remain suspended near the road surface longer. This may reduce costs associated with reapplication of ice melters. FreezGard Cl Plus and Ice Ban 305 both function with the existing application equipment and storage facilities. They could be easily integrated in KYTC's winter maintenance program. Previous research indicates that the SHRP-based laboratory undercutting test is an adequate substitute for evaluating performance in the field. Nevertheless, field testing is strongly recommended before large-scale implementation.

REFERENCES

1. Weather Atlas. “Climate Kentucky, USA.” https://www.weather-us.com/en/kentucky-usa-climate
2. Blandford, B., E. Lammers, and E. Green. (2017). Snow and Ice Removal Route Optimization in Kentucky. *Kentucky Transportation Center Research Report.* 1577. https://uknowledge.uky.edu/ktc_researchreports/1577/
3. Pelton, A. (2005, December 26). Why do we put salt on icy sidewalks in the winter? *Scientific American.* https://www.scientificamerican.com/article/why-do-we-put-salt-on-icy/
4. Fay, L., M. Akin, S. Wang, X. Shi, and D. Williams. (2010, August). Correlating Lab Testing and Field Performance for Deicing and Anti-icing Chemicals (Phase I). Western Transportation Institute. Clear Roads Pooled Fund. http://clearroads.org/wp-content/uploads/dlm_uploads/00-01-Correlating-Lab-Testing-and-Field-Performance-for-Deicing-and-Anti-Icing-Chemicals.pdf
5. Fanghui L., L. Zargarzadeh, H. J. Chung, and J. A. W. Elliott. (2017). *The Journal of Physical Chemistry B*, *121* (40), 9452-9462. DOI: 10.1021/acs.jpcb.7b07271
6. Murphy, D. (n.d.) Peters Chemical Company. *Breaking the ice.* https://www.peterschemical.com/break-the-ice-comparison-of-ice-melting-chemicals/
7. Hosseini, F. (2015). *Evaluating the Effectiveness of Liquid Organic Anti-icing Chemicals for Winter Road Maintenance.* (Master’s thesis, University of Waterloo, Waterloo, Ontario, Canada).
8. New Hampshire Department of Environmental Services. (2010). *Environmental Fact Sheet: Sodium and Chloride in Drinking Water.* https://www.cambridgema.gov/-/media/Files/waterdepartment/Distribution/ ChloridesEnviroFactSheet.pdf
9. The American Society for the Prevention of Cruelty to Animals. (2018, December 4). *Keeping Pets Safe during Winter: The Dangers of Ice Melts.* https://www.aspca.org/news/keeping-pets-safe-during-winter-dangers-ice-melts
10. Occidental Chemical Corporation. *The Case for Calcium Chloride.* https://www.oxycalciumchloride.com/sidewalk-ice-melting/effective-ice-melting/how-to-melt-ice-effectively/the-case-for-calcium-chloride
11. Houska, Catherine. (2013). *Deicing Salt—Recognizing the Corrosion Threat.* https://www.imoa.info/download_files/stainless-steel/DeicingSalt.pdf
12. Murphy, D. (n.d.) Peters Chemical Company. *Calcium chloride vs rock salt.* https://www.peterschemical.com/calcium-chloride-vs-rock-salt-which-do-you-use/
13. Melgares, P. (2017, December 18.) Picking the right product is key to melting ice from sidewalks, driveways. *K-State Research and Extension News.* https://www.ksre.k-state.edu/news/stories/2017/12/winter-deicing-landscapes.html
14. HeatTrak. *Comprehensive Comparison of Your Snow Removal Options.* The HeatTrak Homeowner Blog. https://heattrak.com/blogs/homeowner/comprehensive-comparison-of-your-snow-removal-options.
15. Environmental Protection Agency. (2012, April). *Environmental Impact and Benefit Assessment for the Final Effluent Limitation Guidelines and Standards for the Airport Deicing Category.* https://www.epa.gov/sites/production/files/2015-06/documents/airport-deicing_environmental-impact-and-benefit-assessment-final-2012.pdf
16. National Center for Biotechnology Information (2021). PubChem Compound Summary for CID 517045, Sodium acetate. https://pubchem.ncbi.nlm.nih.gov/compound/Sodium-acetate.

17. Snow & Ice Salt & Chemicals Unlimited, LLC. (2016, January 4). *Sodium Acetate Biodegradable Ice Melt: Environmentally Safe Deicer.* https://snowicesalt.com/sodium-acetate-biodegradable-ice-melt/
18. American Chemical Society. (2007, August 8). Potato Chip Flavoring Boosts Longevity Of Concrete. *ScienceDaily*. www.sciencedaily.com/releases/2007/08/070806101941.htm
19. Kenney Machinery Corporation. *Best Practices for Using Ice Melt for Facilities Managers.* https://kenneymachinery.com/ice-melt/ice-melt-products/
20. Olek, J., A. Janusz, J. Jain, and W. Ashraf. *Investigation of Anti-Icing Chemicals and Their Interactions with Pavement Concretes.* Publication FHWA/IN/JTRP-2013/24. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2013. https://doi.org/10.5703/1288284315226
21. Farkas, J. Q. (n.d.). *Magnesium Chloride vs. Calcium Chloride Ice Melt.* Backyard Boss. https://www.backyardboss.net/magnesium-chloride-vs-calcium-chloride-ice-melt/
22. Nazari, M. H., E. A. Havens, A. Muthumani, and X. Shi. (2019). Effects of Processed Agro-Residues on the Performance of Sodium Chloride Brine Anti-Icer. *ACS Sustainable Chemistry & Engineering 7 (16),* 13655-13667 DOI: 10.1021/acssuschemeng.8b06043
23. Muthumani, A., L. Fay, D. Bergner, and X. Shi. (2015, November). Understanding the Effectiveness of Non-Chloride Liquid Agricultural By-Products and Solid Complex Chloride/Mineral Products. Western Transportation Institute. Clear Roads Report No.13-02. http://clearroads.org/wp-content/uploads/dlm_uploads/FR_CR-13-02_Revised.pdf
24. Yellavajjala, R. K., D. N. Lavadiya, and H. U. Sajid. (2020, July). Corn-Based Deicers. North Dakota State University. http://publications.iowa.gov/33802/
25. Schipani, S. (2019, January 14). Beet juice reduces need for rock salt as de-icer in Canada. *Bangor Daily News.* https://bangordailynews.com/2019/01/14/living/beet-juice-reduces-need-for-rock-salt-as-de-icer-in-canada-could-the-same-work-in-maine/.
26. American Physiological Society. (2018, October 29). Plant-based 'road salt' good for highways but not for insects: Study finds beet juice deicer causes fluid retention and alters organ function in mayflies. *ScienceDaily.* www.sciencedaily.com/releases/2018/10/181029135232.htm
27. Gambino, J., M. Janssen, and H. Pierkes. (1998). *Method for deicing highways using starch-containing compositions.* (U.S. Patent No. 5,849,356). U.S. Patent and Trademark Office. https://patents.google.com/patent/US5849356A/en
28. GMCO Corporation. *Torch IB.* https://www.gmcocorp.com/torch-ib
29. Clear Roads. (2021). Qualified Products List. https://clearroads.org/qualified-product-list/
30. Chappelow, C. C., A. D. McElroy, R. R. Blackburn, D. Darwin, F. G. de Noyelles, and C. E. Locke. (1992, November). *Handbook of Evaluating Test Methods for Evaluating Chemical Deicers*. SHRP-H-332, Strategic Highway Research Program, National Research Council, Washington, D.C. http://onlinepubs.trb.org/onlinepubs/shrp/SHRP-H-332.pdf
31. McElroy, A. D., R. R. Blackburn, and H. W. Kirchner. (1992). Comparative Study of Undercutting and Disbondment Characteristics of Chemical Deicers. *Transportation Research Record 1268.* http://onlinepubs.trb.org/Onlinepubs/trr/1990/1268/1268-021.pdf
32. Shi, X., L. Fay, C. Gallaway, K Volkening, M. Peterson, T. Pan, A Creighton, C. Lawlor, S. Mumma, Y Liu, and T. A. Nguyen. (2009). Evaluation of Alternative Anti-Icing and Deicing Compounds Using Sodium Chloride and Magnesium Chloride as Baseline Deicers—Phase I, Colorado Department of Transportation, Final Report No. CDOT-2009-1.
33. Minnesota DOT. (n.d.). *Field Guide for Testing Deicing Chemicals.* https://www.dot.state.mn.us/maintenance/pdf/research/field-testing-deicers.pdf

34. Chloride Solutions. (2019, August). *Clear Roads – Qualified Product, Product Data Sheet, BIOMELT AG64 Anti-icing/Deicing Fluid.* https://www.dot.state.oh.us/Divisions/ContractAdmin/Contracts/PurchDocs/124-21/Chloride%20Solutions/PDSBiomeltAG64-080819%20-%20CLEAR%20ROADS%20-%20Qualified%20Product%20cs.pdf
35. Scotwood Industries, LLC. FreezGard Zero Liquid Ice Melt Safety Data Sheet. https://scotwoodindustries.com/product/freezgard-zero/
36. Pieper, K. J., M. Tang, C. N. Jones, S. Weiss, A. Greene, H. Mohsin, J. Parks, and M. A. Edwards. (2018, November). Impact of Road Salt on Drinking Water Quality and Infrastructure Corrosion in Private Wells. *Environmental Science and Technology, 52, 24, pp 14078-14087.* https://pubs.acs.org/doi/10.1021/acs.est.8b04709
37. Seaco. Ice B'Gone Magic Safety Data Sheet. https://www.ibgmagic.com/ibg-magic-liquid
38. Earth Friendly Chemicals. (2015). Ice Ban 305 Safety Data Sheet. https://scotwoodindustries.com/wp-content/uploads/2016/12/IceBan-SDS.pdf
39. Cargill. (n.d.). *How do cold temperatures affect liquid deicer in storage?* https://www.cargill.com/how-do-cold-temperatures-affect-liquid-deicer-in-storage
40. Compass Minerals. FreezGard Cl Plus Product Data Sheet. https://freezgard.com/sites/default/files/freezgard_ci_plus.pdf
41. SNI Solutions. (2014). BioMelt AG 64 Safety Data Sheet. https://www.dot.state.oh.us/Divisions/ContractAdmin/ Contracts/PurchDocs/124-21/ChloSolu01/SDS%20BiomeltAG64-062014.pdf
42. SynaTek Solutions. (2017, December 8). *Greener Grounds: Searching for Environmentally Friendly Solutions to Ice and Snow.* https://synateksolutions.com/ice-melt/greener-grounds-searching-for-environmentally-friendly-solutions-to-ice-and-snow

VITA

EDUCATION

University of Kentucky

Bachelor of Civil Engineering, 2017

Bachelor of Chemistry, 2015

WORK EXPERIENCE

Research Engineer, 2017 – present

Kentucky Transportation Center, University of Kentucky

SCHOLASTIC AND PROFESSIONAL HONORS

Sweet Sixteen High Value Research Project, AASHTO Research Advisory Committee. "Snow and Ice Removal Route Optimization in Kentucky." September 2018.

Outstanding Student Paper Award, 1st place, Southern District Institute of Transportation Engineers. "Applicability of Zipper Merge versus Early Merge in Kentucky Work Zones." April 2017.

PROFESSIONAL PUBLICATIONS

Lammers, Erin; Staats, William; Agent, Ken. "Evaluation of Orange Pavement Striping for Use in Work Zones." *Research Report KTC-21-03/FRT-227-1F*. February 2021.

Van Dyke, Chris; Jerin, Tasnuba; Albright, Nancy; Blandford, Ben; Lammers, Erin; Kreis, Doug. "Rapid Diagnostic Framework for Assessing Bridge and Culvert Sensitivity to Hydraulic Forcing." *ASCE: Natural Hazards Review*. February 2021.

Blandford, Benjamin; Albright, Nancy; Van Dyke, Chris; Lammers, Erin; Schurman, Scott. "Kentucky Pilot Project on Asset Management, Extreme Weather, and Proxy Indicators: Final Report." *Federal Highway Administration.* February 2019.

Lammers, Erin; Agent, Ken; Green, Eric. "2019 Safety Belt Usage Survey in Kentucky." *Research Report: KTC-19-30/KSP1-17-1F.* September 2019.

Blandford, Benjamin; Lammers, Erin; Green, Eric. "Snow and Ice Removal Route Optimization in Kentucky." *Transportation Research Record: Journal of the Transportation Research Board.* September 2018.

Blandford, Benjamin; Lammers, Erin; Green, Eric. "Snow and Ice Removal Route Optimization in Kentucky." *Research Report: KTC-17-18/SPR16-529-1F.* August 2017.

Green, Eric; Staats, William; Lammers, Erin; Wang, Teng. "Coaxing HIS Data from Mandli Pavement Scans." *Research Report: KTC-17-26/SPR17-548-1F.* February 2018.

Lammers, Erin; Pigman, Jerry; Howell, Brian; Kirk, Adam. "Applicability of Zipper Merge Versus Early Merge in Kentucky Work Zones." *Research Report: KTC-17-27/SPR16-526-1F.* December 2017.

NAME: Erin Lammers